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TECHNICAL MEMORANDUM 1

STATIC, BALLISTIC, AND IMPACT BEHAVIOR OF GLASS/GRAPHITE DRIVE SHAFTING

By

I. E. Figge, Sr.

June 1972

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY
RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

US ARMY MATERIEL COMMAND

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13. ABSTRACT

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II

ABSTRACT

Limited static tests on damaged scale-model HLH 4.5-inch-diameter ±45° glass/±5° graphite drive shaft sections at 150°F indicated that the shafts are not capable of meeting the design requirement of the HLH. Low-energy impacts (ball drops) produced catastrophic brittle failure of the graphite material. Ballistic damage was localized to the impact area but resulted in a strength reduction factor of approximately 1.75.

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INTRODUCTION

Drive shafts fabricated from advanced composite materials appear to offer the potential of providing reduced weight and of requiring fewer support bearings than their metallic counterparts. However, before the advanced composite drive shafts become operational, the static, dynamic, and impact behavior must be evaluated.

The Boeing Company, Vertol Division, under the Heavy Lift Helicopter – Advanced Technology Concepts (HLH – ATC) Program, initially developed an all-graphite subscale drive shaft for evaluation. Ballistic tests indicated only localized damage upon impact. However, typical handling damage such as a wrench dropped on the shaft produced catastrophic failure, the failure mode being that of classic brittle failure. As a result of this problem, Boeing redesigned the shaft using ±45° glass tape outer wraps to provide torsional strength and ±5° HTS graphite to provide bending stiffness.

This memorandum summarizes the static and ballistic tests of five scale-model shaft sections that were conducted at the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory.

FABRICATION AND PREPARATION FOR TEST

Six shaft sections were fabricated by Boeing-Vertol. The sections were nominally 4.5 inches in diameter and 18 inches in length. The following materials and orientations were used on the six specimens:

Scuff cloth	dry nylon (0.007 inch thick) O.D.
Outer wrap	4 plies ±45° 1002-S glass tape
Inner wrap	8 plies ±5° HTS graphite tape

Specimen 5 (tested entirely at Boeing-Vertol) and 6 had an additional inner ply of XP251S glass oriented at 90° (circumferential). This ply was added to specimens 5 and 6 to increase the buckling failure loads.

The shaft sections were fabricated by placing a bag over a male mandrel, laying the plies of material, placing the mandrel in a female mold, pressurizing the bag, and allowing the specimens to cure at the recommended temperature and pressure. This technique resulted in obvious fiber wash in the ±45° glass plies.

Specimens 1 and 5 were then subjected to low-energy impact (ball drop) tests in preparation for the subsequent tests. A 12-pound steel rod with a 1.4-inch spherical end was dropped onto the specimens from heights ranging from 3 inches to 3 feet. Every effort was made to have the impacts normal to the specimens.

TEST EQUIPMENT AND PROCEDURES

The specimens were subjected to testing as follows:

Specimen	Test
1	Static
2	Static
3	Static
4	Ballistic & Static
5	Static (by Boeing-Vertol)
6	Static

Static tests were conducted in a torsion fixture developed at the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory (Figure 1). The test setup is shown in Figure 2. Pressures were monitored with a pressure gage that was accurate to within ±1 percent. The pressures were calibrated against torque. Temperature was applied to the shaft sections by a series of heat lamps and was monitored at six locations on the sections by thermocouples. Temperatures were stabilized to within ±10°F of the required temperature for approximately 10 minutes prior to testing. Inner and outer steel end fittings were bonded to the specimens with Epiphen 825A adhesive to introduce the torque. A specimen with end fittings is shown in Figure 3.

For the ballistic testing, the shaft section was mounted in the torsion fixture and preloaded to 15,000 inch-pounds at a temperature of 130°F. It was then impacted with fully tumbled .30 caliber ball ammunition at a velocity of approximately 1800 fps. Tumbling of the projectiles was achieved with a smooth-bore rifle with the barrel end cut at an angle.

Photographic records of the static and ballistic tests were taken with a 35mm camera operating at 9,000 frames per second.

TEST RESULTS

Ball drop tests produced gross delamination between the glass and graphite in specimen 1. The degree of delamination was clearly outlined and appeared as a typical glass delamination. Ball drop test heights greater than 3 inches had caused complete lengthwise cracking of the ±5° graphite in conjunction with nonconcentricities of approximately 0.10 inch. This nonconcentric condition indicates the possibility of detrimental residual stresses due to the fabrication technique. Internal damage due to the ball drop is shown in Figure 4.

Damage due to ballistic impact is shown in Figure 5. The ballistic damage was confined to the impact area. As observed in previous programs, the damage on the exit side of the shaft was significantly greater than on the entrance side. The observable external damage is considered to be typical.

In the static tests, all shafts failed in a buckling mode (Figure 6) with the exception of specimen 6. The typical interior failure mode is shown in Figure 7. There were no obvious indications of load drop-off prior to failure. In all specimens, clearly audible cracking was evident throughout the testing. Cracking was heard at loads as low as 10 percent of failure loads.

Specimen 6 failed in the grip bond at 36,500 inch-pounds. The shaft was rebonded to the end fitting and pinned with eight 1/8-inch drill rods equally spaced around the circumference of the shaft. Retest of the shaft again produced failure in the end fittings at 32,000 inch-pounds. The specimen was then shortened to 16-1/2 inches, ends were again rebonded and pinned with four 1/4-inch-diameter pins, and the test was rerun. The specimen was loaded to 90 percent (49,500 inch-pounds) of the predicted ultimate torque without failure. The specimen was then cycled between 0 and 16,700 inch-pounds (maximum operating torque) for 125 cycles. At this point, an attempt was made to determine the ultimate strength of the shaft. Again the grip bond failed, but at a considerably higher value of torque than in the previous tests (75,000 inch-pounds). The shortened length of the shaft in the latter test probably contributed to the higher failure loads.

Although the grip failures are representative of a failure mode that could be anticipated under operating conditions, these three data points for the failures were not included in the averages since the purpose of these tests was to evaluate the shaft behavior and not the end fittings.

Table I summarizes the test results.

TABLE I. TEST RESULTS			
		Static Test Condition	
Specimen	Condition Prior to Static Test	Temp	Failure Torque (in.-lb)
1	12-lb ball drop at 3, 6, 12, 24, and 36 in.	150°F	26,000
2	Undamaged	150°F	48,000
3	Undamaged	150°F	36,000*
4	Fully Tumbled ball, 1,800 fps, 130°F, preloaded to 15,000 in.-lb	130°F	26,000
5**	a. Undamaged	RT	49,300 (no failure)
	b. 12-lb ball drop, single drop from 36 in.	RT	24,000 (retest)
6	a. Undamaged	RT	Adhesive failure in grips at 36,500
	b. Rebonded grips, eight 1/8-in.-dia pins	RT	Adhesive failure in grips at 32,000
	c. Shaft shortened to 16.5 in., rebonded grips, four 1/4-in.-dia pins	RT	49,500 (no failure); 125 cycles at 0 to 16,700 in.-lb, adhesive failure in grips at 75,000 in.-lb

*Fixture support failed during test, causing fixture to deflect approximately 0.2 inch on one side. Load on shaft dropped off until deflection stabilized; load then increased linearly to failure.

**Tested at Boeing-Vertol, but included here as a data point.

DISCUSSION

Scaled loads for the subscale 4.5-inch-diameter shaft were as follows:

Design operating torque	14,700 ±2,205 in.-lb
Design limit torque	22,050 in.-lb
Design ultimate torque*	33,070 in.-lb

The design requirements for the HLH call for a full-scale shaft capable of operating at 180°F at limit torque after receiving ballistic damage. To evaluate the potential of the Boeing subscale design to meet full-scale requirements, the subscale data (18-inch length) were extrapolated to a representative full length of 95 inches by using the data from this program and data obtained from tests conducted by Bell Helicopter on both carbon[1] and boron[2] shafts. Table II summarizes Bell's results.

TABLE II. BELL DATA ON BORON AND CARBON DRIVE SHAFT

Material	Test Torque (in.-lb)	Condition Prior to Test	Temp (°F)	Diameter (in.)	Length (in.)	
Carbon	39,500	Undamaged	RT	4.95	12	short shaft
	42,500	Undamaged			12	
	20,200	Ballistically damaged by untumbled .30 cal AP round at 2,750 fps			12	
	24,700	Undamaged			92	long shaft
Boron	39,600	Undamaged		5.00	12	short shaft
	43,400	Undamaged			12	
	19,800	Ballistically damaged by untumbled .30 cal AP round at 2,750 fps			12	
	20,500	Undamaged			97	long shaft

Based on the Bell and Eustis Directorate tests, the data were averaged for each material, and ratios between undamaged and damaged (ballistic and ball drop) specimens and short and long shafts were obtained. The results are shown in Table III.

*Based on a mean (mean -3σ) allowable = 65,400 in.-lb and a design allowable of 47,500 in.-lb.

TABLE III. DATA SUMMARY

Material	(Undamaged Torque) / (Damaged Torque)	(Short Shaft Torque) / (Long Shaft Torque)
Carbon	2.03	1.66
Boron	2.02	2.02
Glass/Graphite @ 150°F	1.75	–

The data from Table III for the carbon and boron were averaged to obtain a representative ratio between short and long shaft torques. The ratio of undamaged to damaged torque for glass/graphite at 150°F was considered to be representative for the purpose of extrapolation.

Assuming that these ratios are representative of the strength reduction factor and size effect, respectively, and that they interact, they were applied to the Boeing short-shaft data to obtain long-shaft failure torque (4.5-inch diameter) with either ballistic or impact damage at 150°F as follows:

$$T_{\ell s} = \frac{A}{\left(\frac{B + C}{2}\right) \times D}$$

$$T_{\ell s} = \frac{44{,}400}{\left(\frac{1.66 + 2.02}{2}\right) \times (1.75)} = 13{,}800 \text{ in.-lb}$$

where $T_{\ell s}$ = Extrapolated long shaft failure torque at 150°F
A = Average undamaged short shaft torque from Table I
B = Ratio of short shaft torque to long shaft torque for carbon
C = Ratio of short shaft torque to long shaft torque for boron
D = Ratio of undamaged torque to damaged torque for glass/graphite at 150°F

The value of 13,800 inch-pounds, although based on very limited data, is substantially below the limit torque and slightly below the operating torque. Thus, on this basis, it can be speculated that a full-length 4.5-inch-diameter shaft of the current design would not meet the design requirements as stipulated.

Projected total HLH drive system weight savings for the composite drive shaft over that of an optimized all-aluminum drive shaft is 106 pounds for specimens 1 through 4 and 75 pounds for specimens 5 and 6. The composite shafts themselves (total system) weigh approximately 51 pounds more than their metallic counterparts. The total system weight savings are achieved by reducing the number of bearings required for the composite shaft as compared to the metallic shaft.

SUMMARY AND CONCLUDING REMARKS

Limited static tests on ballistically or impact-damaged drive shaft sections at 150°F indicate that the ±45°glass/±5° graphite design selected by Boeing is not adequate to meet the design requirements of the HLH.

When the scale-model shafts are extrapolated to a full-size shaft of 9 inches O.D. with a 0.2028-inch wall thickness, the total composite system represents a 75-pound weight savings over a conventional aluminum system. The cost effectiveness of a system of the HLH size with such a small weight savings and high material and fabrication costs becomes questionable.

It is believed that the shaft concept that was tested has not been optimized to meet the design criteria established. It is further believed that a shaft system that has an optimized fiber/resin system will project a greater weight savings than that tested. The residual stresses as evidenced by specimen 1's going out of round after impact must be understood and controlled prior to the optimization of a shaft design.

The limited data that are available for drawing conclusions clearly indicate that a high degree of risk is apparent with the shaft configuration tested. Only four data points on the undamaged shaft strength are available, and the scatter of these points is large.

A better understanding of the ballistic and impact behavior of advanced composites, along with improved fabrication techniques and material combinations, is required to take full advantage of advanced composite materials for drive shaft application.

LITERATURE CITED

1. CARBON COMPOSITE HELICOPTER TAIL ROTOR DRIVESHAFT, prepared by Whittaker Corporation, Advanced Structures Division, for Bell Helicopter Company, Fort Worth, Texas, under Contract R-268702, July 1970.

2. Zinberg, H., and Symonds, M. F., THE DEVELOPMENT OF AN ADVANCED COMPOSITE TAIL ROTOR DRIVESHAFT, Preprint No. 451, presented at the 26th Annual National Forum of the American Helicopter Society, Washington, D. C., June 1970.

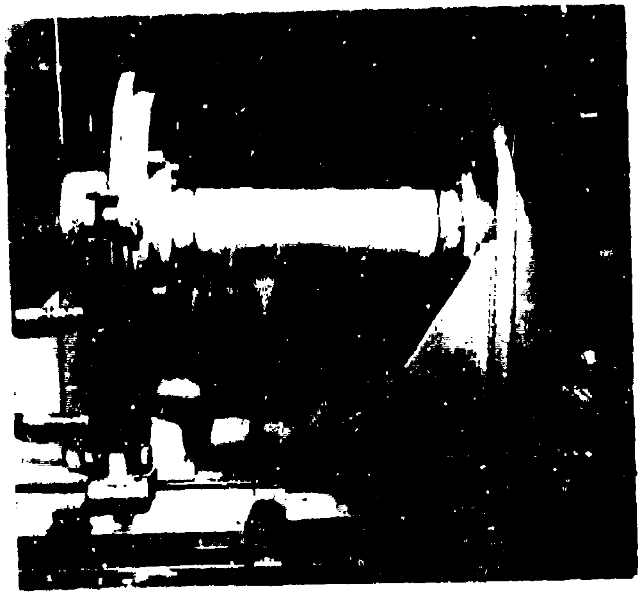


Figure 1. Hydraulically Operated Torsion Fixture.

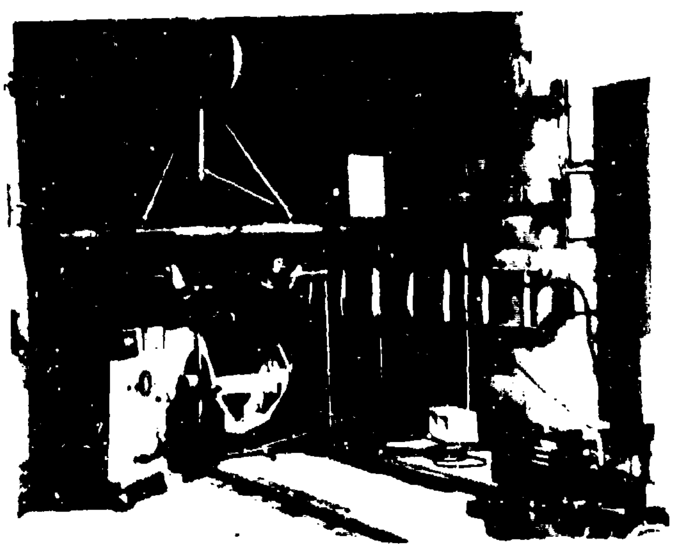


Figure 2. Ballistic Test Setup.

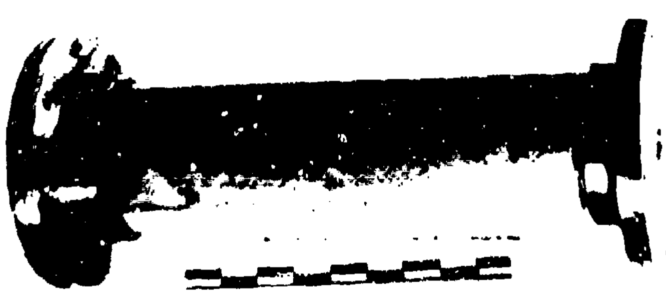
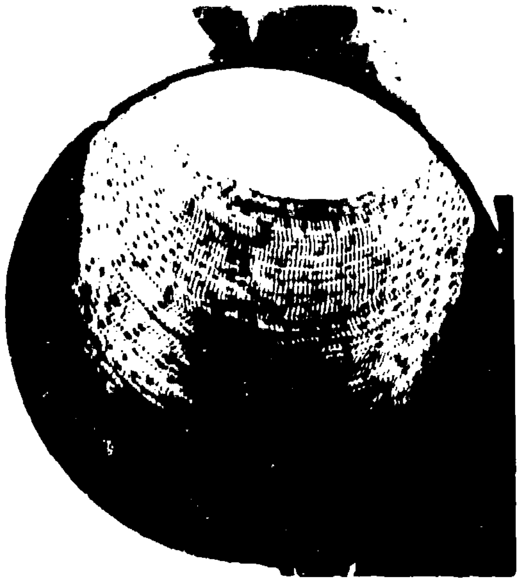
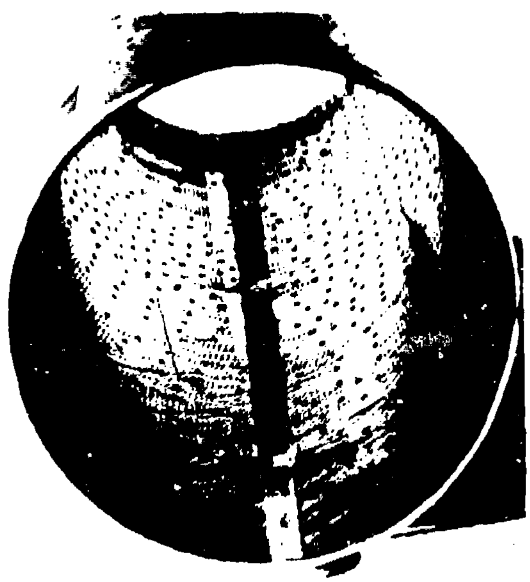


Figure 3. Specimen With End Fittings.

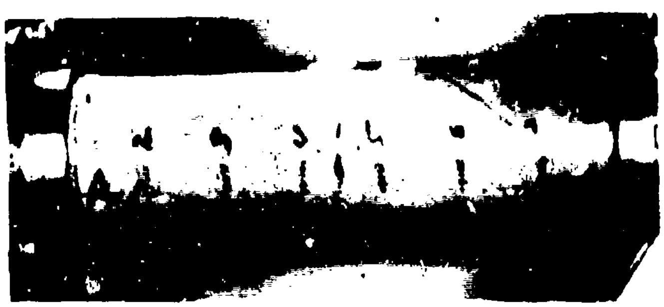


View A



View B

Figure 4. Internal Cracking From 12-Pound Ball Drop Tests (Multiple Drops).



Entrance Damage

Exit Damage

Figure 5. Damage From .30 Caliber Ball Round at 1800 Feet Per Second.

Ballistic Impact 12-Pound "Ball Drop" Undamaged

Figure 6. Typical Failure Modes at 150°F.

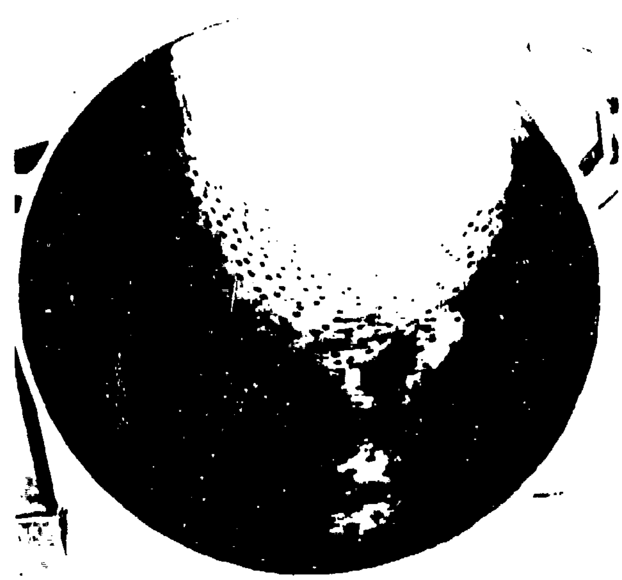


Figure 7. Typical Interior Failure Mode.

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Design ultimate torque[1]	33,070 in.-lb

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[1] Based on a mean (mean -3σ) allowable = 65,400 in.-lb and a design allowable of 47,500 in.-lb.

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